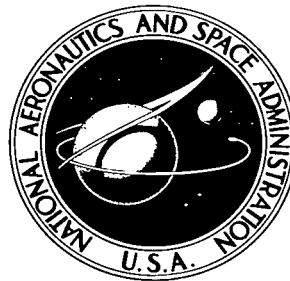


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KIRTLAND AFB,A SIMULATOR STUDY OF PILOT CONTROL
OF REMOTE ORBITAL DOCKING OF LARGE
ATTITUDE-STABILIZED COMPONENTS*by Donald R. Riley and William T. Suit**Langley Research Center**Langley Station, Hampton, Va.*



**A SIMULATOR STUDY OF PILOT CONTROL OF REMOTE ORBITAL
DOCKING OF LARGE ATTITUDE-STABILIZED COMPONENTS**

By Donald R. Riley and William T. Suit

**Langley Research Center
Langley Station, Hampton, Va.**

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A SIMULATOR STUDY OF PILOT CONTROL OF REMOTE ORBITAL DOCKING OF LARGE ATTITUDE-STABILIZED COMPONENTS

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Langley Research Center

SUMMARY

A brief fixed-base-simulator study has been made to determine the ability of human pilots to perform orbital docking between two spherical tanks from a manned spacecraft positioned some distance away. All three vehicles were assumed attitude stabilized. The pilot was given translational control of the manned spacecraft and of one of the remotely located tanks by means of simple on-off reaction jets. Guidance cues were obtained from two light spots, displayed on a cylindrical screen, that symbolized the two fully illuminated spherical tanks. In the simulator, docking was considered complete when the two light spots were the same size and were positioned tangent to each other directly ahead of the pilot. The results of the investigation indicated that pilots could complete remote docking with acceptable terminal conditions except for longitudinal positioning. An upper limit to the energy exchange between tanks at contact was shown by the data for the three velocity components between tanks which were found to be of small magnitude and invariant with spacecraft range. Data on the longitudinal misalignment between tanks, however, indicated that, as range of the manned spacecraft was increased above a given value, docking success decreased.

INTRODUCTION

One of the proposed schemes of achieving early manned interplanetary flight uses the approach in which the final space vehicle is constructed from several components that are placed in orbit about the earth as separate payloads. One of the main features of such a scheme is that some flights could be undertaken at a much earlier date if launch boosters now under development were used, rather than more powerful launch vehicles to be designed in the future. Although this procedure alleviates the booster requirements, it introduces the complication of assembling the components in space.

In an effort to assess some of the problems that might be encountered by using this approach to interplanetary flight, a preliminary investigation was undertaken of pilot-controlled orbital maneuvers necessary for assembly of various payloads after they are in orbit and in near proximity. A fixed-base simulator was used and three orbiting

vehicles consisting of a manned spacecraft and two unmanned spherical tanks were considered. As a means of minimizing hazards that might be encountered in assembling potentially dangerous vehicle components in space, remote docking was employed; and the docking maneuvers between the two tanks were performed with one tank under the command of a pilot in a spacecraft positioned at distances of from 100 to 400 feet (30 to 120 meters).

Pilot-controlled docking of a manned spacecraft and an orbiting space vehicle has been the subject of a number of papers (for example, refs. 1 to 7) primarily in preparation for the rendezvous and docking missions scheduled for Project Gemini. Reference 6 presents typical results for a two-body system obtained by using the same fixed-base simulator employed for the present study. In general, the feasibility of pilot-controlled docking using visual observation of the target for guidance has been verified by these investigations and by actual space flights (flights of Gemini VIII through XII). The present paper examines this visual-manual scheme for a three-vehicle situation.

SYMBOLS

Both the U.S. Customary Units and the International System of Units (SI) are employed herein. Factors relating these two systems are given in reference 8.

The system of axes employed for the present study is shown in figure 1.

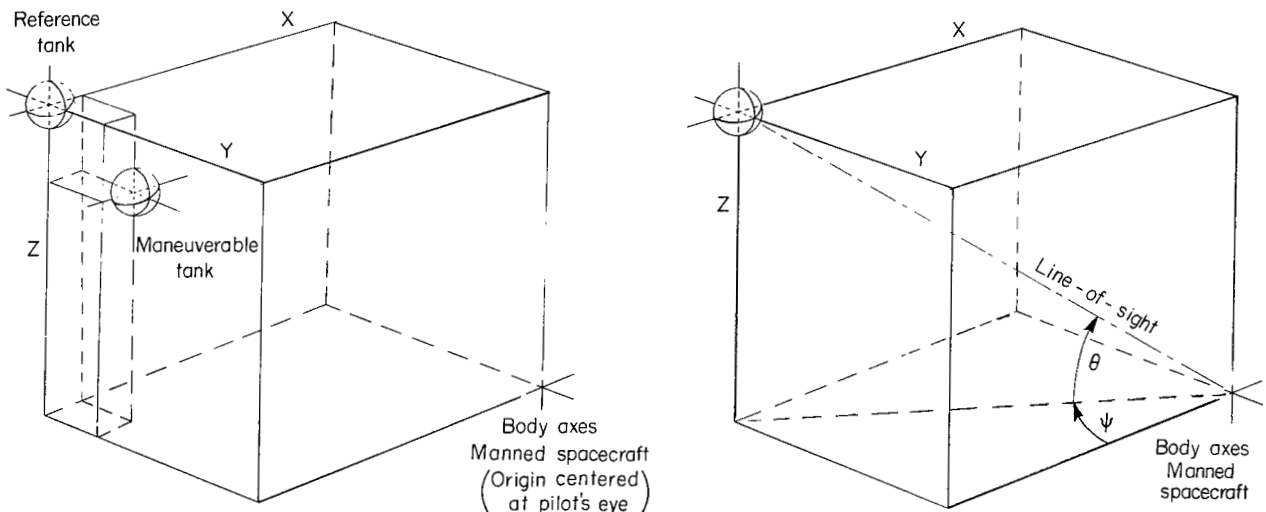


Figure 1.- Axis system used. Positive values of displacements and line-of-sight angles indicated.

X,Y,Z right-handed system of reference axes with origin located at the center of the nonmaneuverable spherical tank

x,y,z distances along the X-, Y-, and Z-reference axes, respectively, feet or meters

ψ, θ	azimuth and elevation angles, respectively, of the pilot's line of sight, with respect to the spacecraft body axes, degrees or radians (see fig. 1)
T/m	ratio of translational jet thrust T to vehicle mass m , feet/second ² or meters/second ²
ΔV	characteristic velocity increment (measure of fuel consumption), feet/second or meters/second
D	spherical tank diameter, feet or meters

Subscripts:

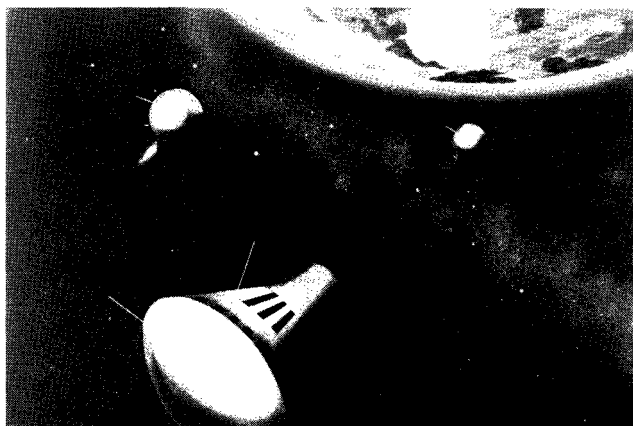
h, v	docking in horizontal and vertical directions, respectively
s, t	manned spacecraft and maneuverable tank, respectively
X, Y, Z	associated with X, Y, Z axes, respectively

A dot over a symbol denotes the derivative of the quantity with respect to time.

SIMULATION OF THE PHYSICAL PROBLEM

The physical problem under consideration is illustrated in figure 2. A manned spacecraft and two unmanned 10-foot-diameter spherical tanks in orbit and in near proximity are represented. The vehicle attitudes are assumed to be stabilized so that the body axes of all three vehicles remain parallel. The manned spacecraft and one spherical tank are equipped with maneuver thrusters providing each of the two vehicles with translation capability along the three body axes.

Translation of both vehicles is commanded by the pilot in the manned spacecraft. The remaining spherical



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Figure 2.- Artist's illustration of the three-vehicle orbital docking problem considered.

Figure 4.- Pilot's cockpit and projection system.
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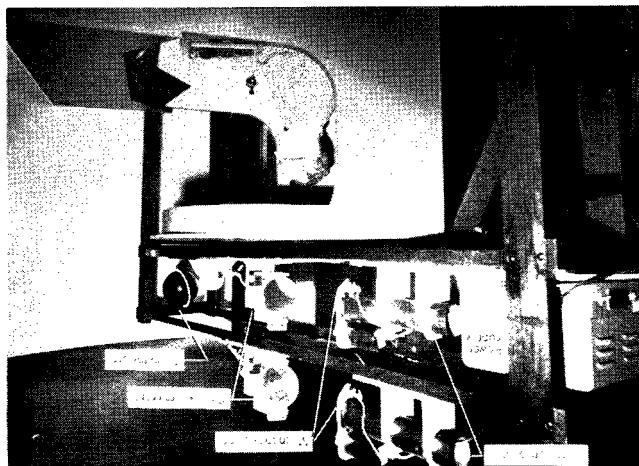
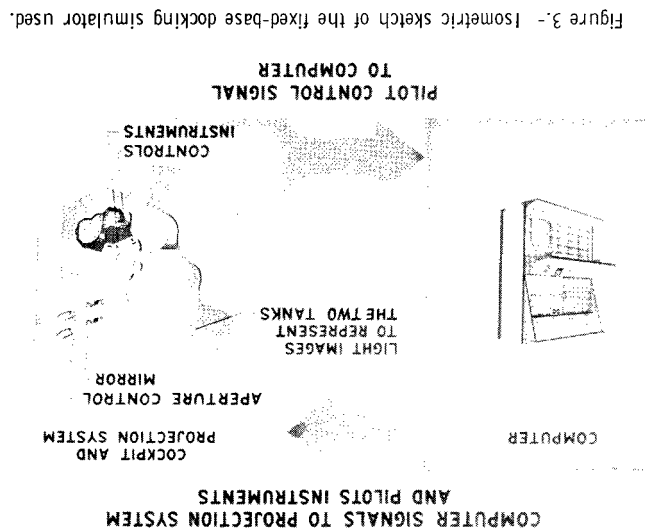


Figure 3.- Isometric sketch of the fixed-base docking simulator used.



tank (referred to herein as the reference tank) is assumed to be nonmaneuverable. The pilot is required to maneuver both the controllable tank and the manned spacecraft until he effects the docking between the two spherical tanks at some distance from the manned spacecraft.

Figure 3 illustrates the physical setup used for the simulation. The pilot's display consisted of two light spots of variable size, projected on a 16-foot-diameter cylindrical screen, to represent the two 10-foot-

diameter spherical tanks. The positions and sizes of the spots were controlled by an analog computer which solved the equations of relative motion between the two tanks and the manned spacecraft. The projection system consisted of two cylindrical tubes which contained 25-watt point light sources and mechanical apertures for controlling the size of the light spots. Two front-surfaced mirrors, each servo-driven about two axes, positioned the light spots on the screen. For identification, the maneuverable tank was displayed as a yellow spot and the reference tank as a white spot. The screen completely enclosed the pilot's cockpit and the display area was impenetrable to light. A small planetarium provided a star background. The pilot's field of view in the simulator was 48° vertically and 180° horizontally. A closeup photograph of the pilot's cockpit and the projection system is presented as figure 4.

Only one level of spot illumination was used in the simulator tests. Light-spot luminance was estimated to be of the order of 1 foot-lambert (3.43 candelas/meter²). For actual space flight, the luminance of orbiting vehicles can vary over a wide range depending on the source of illumination of the vehicle. References 9 and 10 provide some information on the visibility of an object in space. Reference 9 indicates that the shape of vehicles with light, flat finishes will be discernible so that a fully illuminated spherical tank some distance away would appear as a circular disk.

EQUATIONS OF MOTION

For the three-vehicle situation considered herein, one of the orbiting tanks was considered nonmaneuverable (reference tank) and a reference coordinate axes system was centered in this tank. (See fig. 1.) The translational equations of motion used for the manned spacecraft and maneuverable tank relative to the reference axes are as follows:

Maneuverable tank

$$\frac{T_{X,t}}{m_t} = \ddot{x}_t$$

$$\frac{T_{Y,t}}{m_t} = \ddot{y}_t$$

$$\frac{T_{Z,t}}{m_t} = \ddot{z}_t$$

Manned spacecraft

$$\frac{T_{X,s}}{m_s} = \ddot{x}_s$$

$$\frac{T_{Y,s}}{m_s} = \ddot{y}_s$$

$$\frac{T_{Z,s}}{m_s} = \ddot{z}_s$$

Additional velocity and displacement acceleration terms involving the orbital angular rate usually appear in these expressions for rendezvous maneuvers. (For example, see refs. 11 and 12.) These terms were omitted herein because the values were small and also because the pilot provides closed-loop control which negates any long-time accumulated effects on positions and velocities that additional terms produce. In addition, since total fuel consumption is small for the docking maneuvers considered, vehicle mass changes due to thrusting were neglected.

CONTROL CHARACTERISTICS

The translational motions of the manned spacecraft and maneuverable tank were assumed to be produced by instantaneously reacting on-off thrusters. Thruster outputs were commanded by the pilot by means of two identical three-axis fingertip controllers, one for each vehicle. The pilot controlled the movable tank with the right-hand controller and the manned spacecraft with the left-hand controller. The controllers were on-off

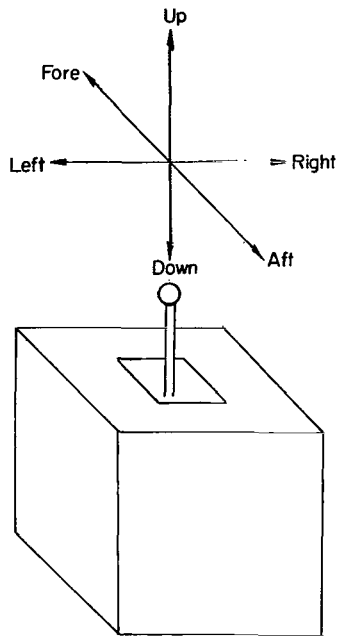


Figure 5.- Sketch of translation controller.

spring-centered devices, and thruster acceleration level T/m used in all tests was 0.6 ft/second^2 (0.2 m/sec^2). One of the controllers is visible in the pilot's left hand in figure 4.

Construction of the controllers permitted acceleration commands to be applied along each vehicle axis individually or simultaneously. (See fig. 5.) Since the controllers required a deflection of at least $3/8$ inch (0.9 cm) to effect a command, a visual indication that the reaction jets were firing was supplied to the pilot by three dim red indicator lights for each vehicle. These lights (one for each axis) were arranged horizontally and located just above each controller on the instrument panel.

PILOT'S TASK

Using only visual cues for guidance, the pilots were required to take control of both the manned spacecraft and the maneuverable tank from the initial conditions and to perform the necessary maneuvers so that a docking would be effected between the two tanks when they were directly ahead of, but at some distance from, the manned spacecraft. No restraints were placed on fuel and flight time. Prior to each flight a desired distance between spacecraft and tanks at docking was indicated as a secondary requirement to be fulfilled in only an approximate manner.

In the simulator, docking was defined as that condition at which the two light spots were of equal size and tangent to each other. Both vertical and horizontal dockings were performed during the tests, with the desired orientation specified for each flight. Collision velocities between tanks, which were required for positive coupling, were to be kept low (0.1 to 0.2 ft/sec or 0.03 to 0.06 meter/sec) to prevent tank rupture of the present thin shell structures and to eliminate considerations of massive docking fixtures. At the instant of tangency of the light spots, the pilot terminated the flight and the computer was then interrogated for the terminal conditions.

TESTS

The initial conditions (IC) for the displacements and velocities for the manned spacecraft and maneuverable tank that were employed for 78 flights to obtain the data presented herein are listed in table I.

TABLE I.- INITIAL CONDITIONS FOR FLIGHT DATA*

IC	Maneuverable tank						Manned spacecraft					
	x_t , ft	y_t , ft	z_t , ft	\dot{x}_t , ft/sec	\dot{y}_t , ft/sec	\dot{z}_t , ft/sec	x_s , ft	y_s , ft	z_s , ft	\dot{x}_s , ft/sec	\dot{y}_s , ft/sec	\dot{z}_s , ft/sec
1	100	-150	100	1	1	1	300	100	100	1	1	-1
2	-100	-150	-100	-1	-1	-1	300	100	0	-1	1	0
3	-100	-150	0	0	0	1	300	-100	100	-1	1	0
4	-100	-150	-100	1	1	0	300	100	-100	0	0	1
5	100	-150	-100	0	-1	-1	300	0	0	1	-1	0
6	-100	150	100	1	1	1	200	200	100	-1	1	-1
7	0	-150	-100	0	0	1	200	200	0	-1	1	-1
8	-100	150	-100	1	1	-1	200	200	0	-1	1	1
9	0	-150	100	0	-1	1	200	200	100	1	-1	0
10	0	150	0	0	-1	0	200	200	0	-1	0	1
11	-100	150	100	1	-1	-1	100	300	100	-1	-1	0
12	0	150	100	0	0	0	100	300	100	0	-1	1
13	0	150	100	-1	1	-1	100	300	0	-1	0	0

*Metric equivalents (absolute) for the distances and velocities shown in this table are as follows:

Distance:

100 feet = 30 meters
 150 feet = 45 meters
 200 feet = 60 meters
 300 feet = 90 meters

Velocity:

1 foot/second = 0.3 meter/second

Although all initial conditions were used during the tests, some (IC 1, 2, 3, 6, 7, and 8) were used more frequently than the others. For all initial conditions used, both tanks were completely visible to the pilot at the start of a flight. For all data flights, the authors served as pilots. To verify the reasonableness of the task presented, several test pilots also flew the simulator. Because only a few flights were made by each of these subjects, their results were not included in the data presented.

RESULTS AND DISCUSSION

Piloting Technique

The piloting technique employed by all pilots was to achieve positions of the three vehicles relative to each other so that the final docking maneuvers could be performed

with both tanks located directly in front of the pilot. Ideally, the pilot's line of sight would be along the spacecraft's longitudinal axis (X-axis) and would intersect the point of contact between the tanks at the instant of docking. For terminal maneuvers, this technique conveniently uncoupled the display motions for a given controller movement so that fore-and-aft control inputs adjusted apparent tank size and growth rate, whereas vertical and lateral control inputs adjusted position and velocity of the tanks normal to the line of sight.

At flight initiation, the pilots evaluated the situation presented and applied controls to null any motions tending to increase the separation between the two tanks and between the reference tank and the manned spacecraft. Control inputs were then applied to reposition the spacecraft and maneuverable tank in a way that would place both spherical tanks in front of the pilot. Longitudinal (fore-and-aft) positioning of the tanks and spacecraft was frequently neglected during these initial maneuvers primarily because the apparent relative sizes of the tanks were affected by transverse positioning of the spacecraft and of one tank relative to the other. Only in cases where the difference in apparent size of the tanks was excessive or the range between the spacecraft and the nonmaneuverable tank was considerably larger than desired were fore-and-aft control inputs applied in order to shorten the flight time. Once the angular separation between tanks was small and the line of sight was nearly aligned with the spacecraft's longitudinal axis, fore-and-aft control inputs were applied to position the manned spacecraft at the desired distance from the reference tank and to adjust the range of the maneuverable tank.

A typical flight trajectory obtained by this piloting technique is illustrated in figure 6. Approximately one-quarter of the flight time was spent in gross position changes in order to align the tanks approximately in front of the pilot. For the remaining three-quarters of the flight, the pilot applied short-duration inputs to adjust range and to achieve the desired terminal conditions for docking. For this particular flight an initial closure velocity ($-\dot{x}_S$) existed for the manned spacecraft. Since this velocity was corrective as regards final desired spacecraft range, the pilot permitted it to remain uncorrected for approximately half of the flight.

One other technique was attempted during the test program. This technique eliminated the dependence on size difference for evaluating end conditions at flight termination by requiring the pilot to maneuver the manned spacecraft to two separate locations such that the difference in viewing angles was about 90° , so that essentially a front and then a side view at docking could be attained. This technique was unsuccessful, because the residual velocities of one tank relative to the other were sufficient to result in misalignment during the time interval required to reposition the manned spacecraft. An attempt to shorten the time interval by reducing the difference in viewing angles to about 45° resulted in coupling difficulties between display motions and control movements.

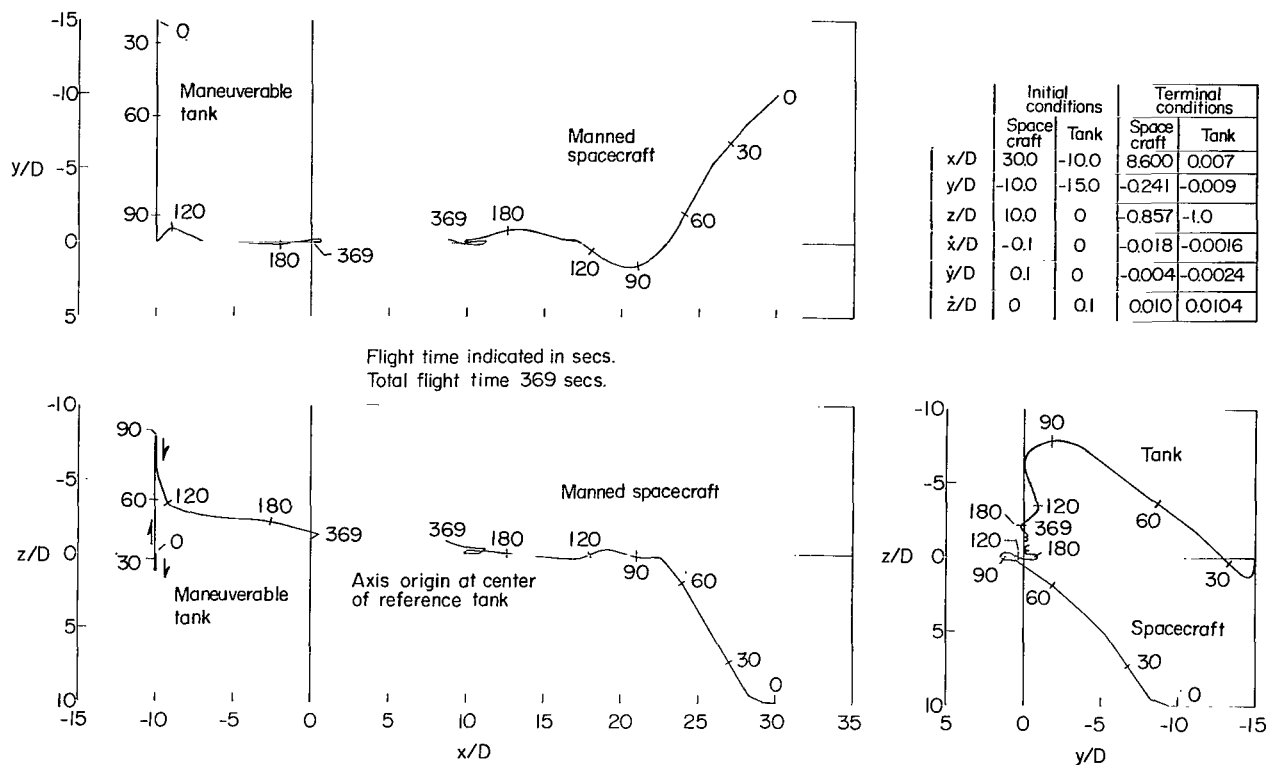


Figure 6.- Typical flight trajectories of manned spacecraft and maneuverable tank culminating in a vertical dock between spherical tanks.

Terminal Conditions

Data of each variable for the manned spacecraft relative to the two tanks and for the maneuverable tank relative to the reference tank are presented in figures 7 to 10. The data are presented as a function of spacecraft displacement from the tanks at docking and as summary curves (percent of total flights as a function of magnitude). Most of the data were obtained for separation distances of about 100 feet; however, sufficient data are available at the larger ranges to illustrate the general data trend with increasing displacement of the manned spacecraft at docking. As a guide in interpreting the results, approximate boundaries are also shown. For most variables, the boundary can be considered as the single-task visual detection threshold multiplied by an arbitrary constant because of the multiple control task.

Manned spacecraft. - The five variables specifying spacecraft displacements and velocities at flight termination are presented in figure 7 as a function of separation distance from the reference tank. The vertical and lateral misalignment data fall in triangular shaped patterns and the approximate boundaries increase linearly with range. Such boundaries result from using line-of-sight angle and rate information. Since this part of the task was considered secondary to the docking between spherical tanks, it

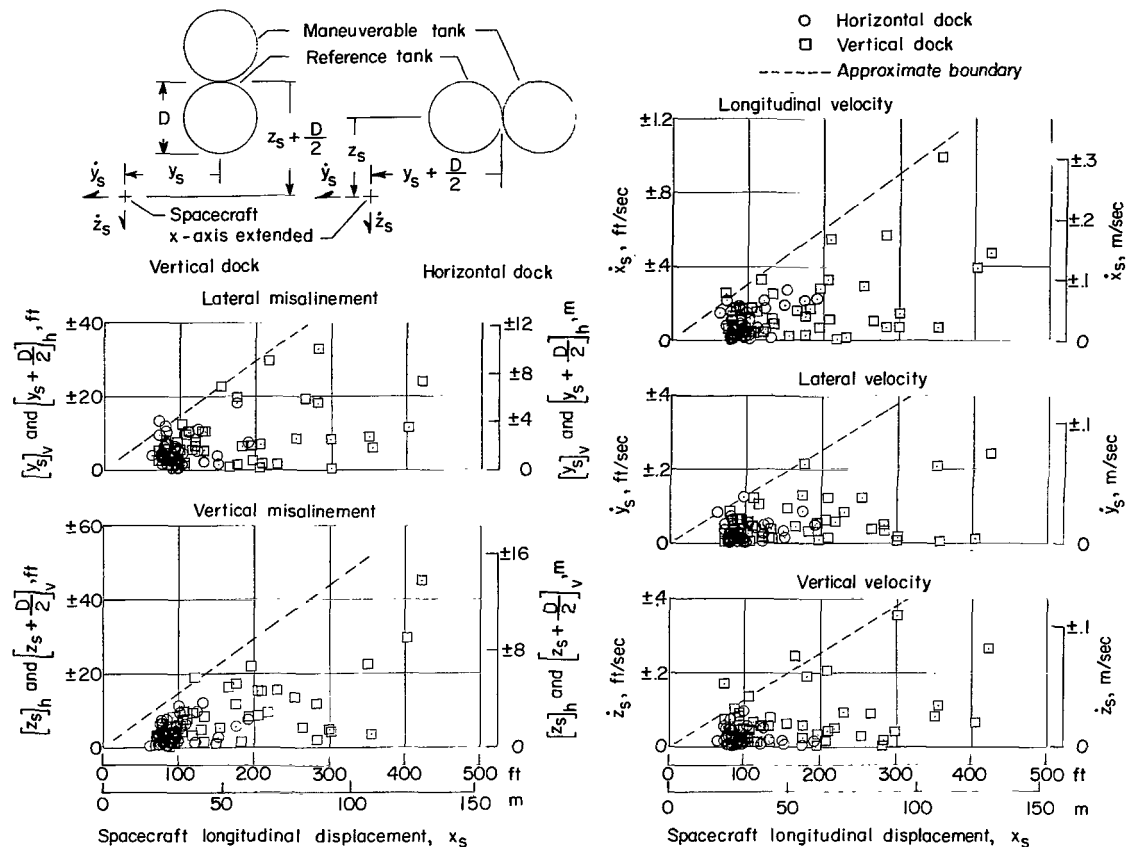


Figure 7.- Terminal conditions for manned spacecraft relative to specified contact point on reference tank (total flights 78).

seems reasonable that spacecraft terminal maneuvers performed by the pilots would be based on azimuth and elevation angles and their angular rates for the line of sight to the proposed contact point between tanks. (Boundaries shown for lateral and vertical misalignment y_s and z_s are identical, as are those for the velocities \dot{y}_s and \dot{z}_s .) The linear boundary for longitudinal velocity \dot{x}_s with displacement x_s is indicative of guidance cues obtained from detection by the pilots of a percentage change in the apparent size of the reference tank after a given interval of time. The particular boundary shown is in excellent agreement with a human's visual threshold for detecting range rate as derived in reference 6 (equation (A-7)) and was anticipated due to the effort expended in trying to null spacecraft longitudinal velocity during the flights. For each of the five variables of figure 7, differences due to horizontal and vertical dockings of the spherical tanks were not apparent in the data.

Summary curves for azimuth and elevation angles (ψ and θ), their rates ($\dot{\psi}$ and $\dot{\theta}$), and range-rate to range ratio (\dot{x}_s/x_s) are presented as figure 8. These data show that comparable results were obtained for the azimuth and elevation angles as well as

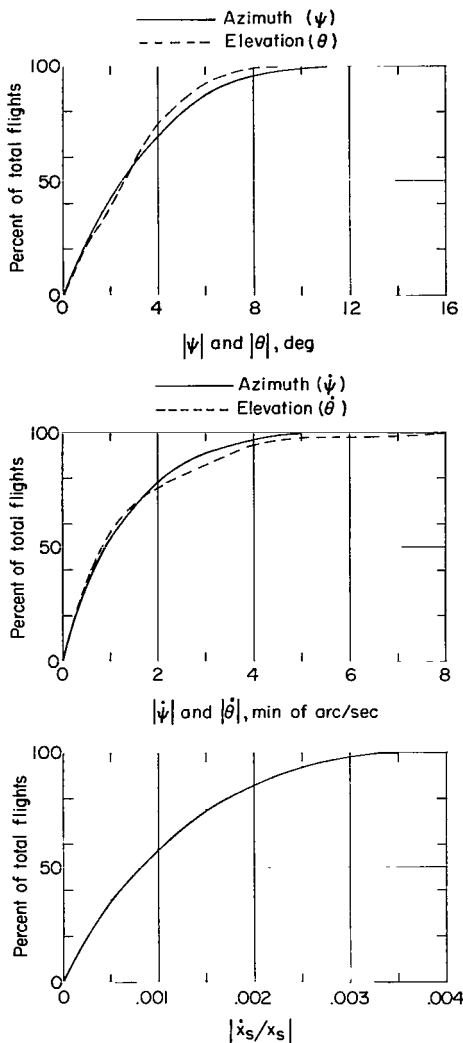


Figure 8.- Summary curves of terminal end conditions for manned spacecraft showing percentage of flights below a given magnitude.

for their corresponding rates. A detailed study of the measurements showed that in about 75 percent of the flights angular rates existing at flight termination were such as to increase the displacement rather than to decrease it. This result illustrates the secondary nature assigned this part of the task. With primary emphasis on the docking between spherical tanks, the pilots permitted the spacecraft to drift with small uncorrected vertical and lateral velocities for fairly long time intervals. Of the five variables, only for range rate was a major effort made to achieve the desired null condition.

Two tanks.- Terminal values for the velocities and displacements for the maneuverable tank relative to the reference tank are shown in figure 9 as a function of distance from the manned spacecraft. Rather than present two groups of data, one for vertical dockings and one for horizontal dockings, a single presentation that eliminates docking direction and pairs the variables according to the task presented the pilot is employed. For example, controlling vertical velocity for a vertical docking ($\dot{z}_{t,v}$) is comparable to controlling horizontal velocity for a horizontal docking ($\dot{y}_{t,h}$) since both are velocities in the principal direction of contact between tanks and the data for these two results have been presented together. Thus, five task variables can be defined with a desired terminal condition specified for each. Because only displacements and velocities normal to the pilot's line of sight are rearranged for

this presentation, an independent examination of the vertical docking data and the horizontal docking data shows a nearly identical spread of magnitudes for each of the three variables involved.

The results in figure 9 show that most data patterns and approximate boundaries are invariant with spacecraft longitudinal displacement and hence are different from the results for the manned spacecraft shown in figure 6. The transverse misalignment boundary is invariant with range because pilots' judgments for control were made with the misalignment expressed as a percentage of apparent diameter of the reference tank. For longitudinal positioning, pilots' judgments were based on the difference in apparent size of

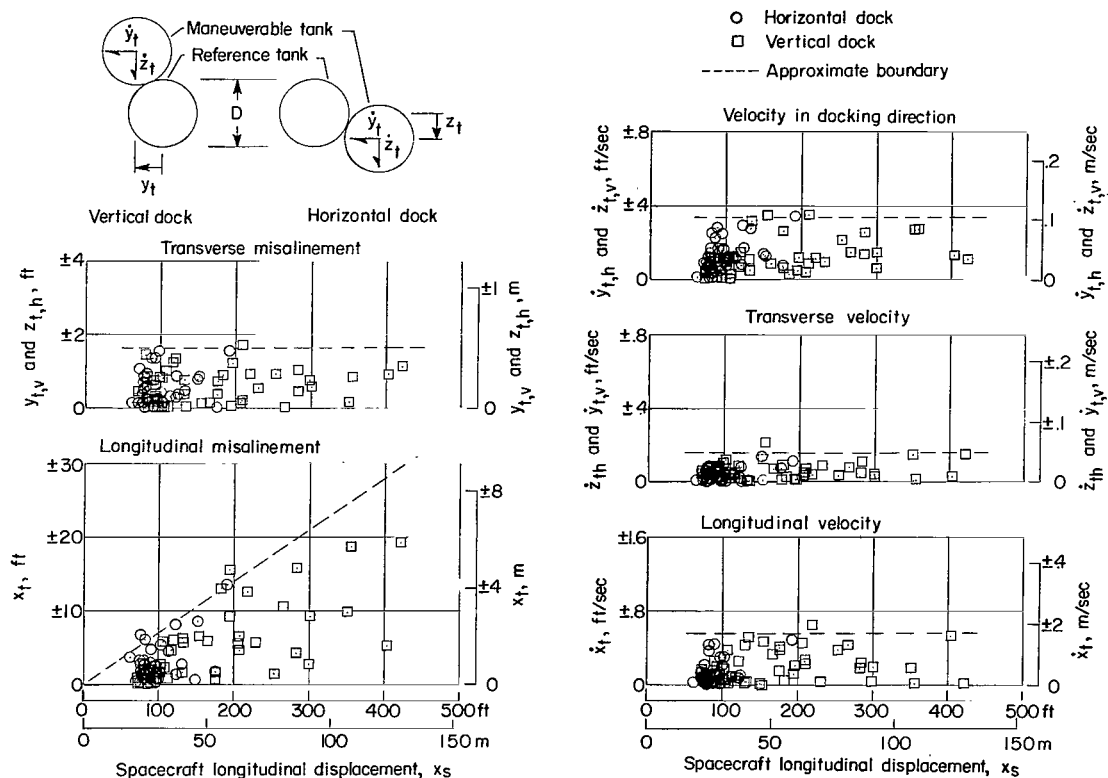


Figure 9.- Terminal conditions for maneuverable tank relative to reference tank (total flights 78).

the two tanks. The linear variation shown for the boundary is equivalent to expressing the difference in apparent diameter of the two tanks as a constant percentage of the apparent diameter of the reference tank. For the three velocity components, only near-minimum control inputs were employed so as to keep the velocity magnitudes low near contact. Judgments of velocity by the pilots as guidance cues near flight termination take the form of detecting differences in displacements after some elapsed time interval. Inasmuch as the intervals are fairly long, because of the multiple control task, such judgments merely indicate that the velocities are of relatively small magnitude. Thus, boundaries invariant with range for the two velocity components normal to the pilot's line of sight seem reasonable and are similar to (but exceed in magnitude) human visual thresholds. The lower value of the boundary for the transverse velocity component ($\dot{y}_{t,v}$ and $\dot{z}_{t,h}$) when compared with the component in the docking direction ($\dot{z}_{t,v}$ and $\dot{y}_{t,h}$) is due to the null condition desired for the transverse velocities, whereas some magnitude was desired for the other component to assure tank coupling. Of all the terminal conditions presented, only the invariant boundary for longitudinal velocity was not expected. The boundary shown was arbitrarily drawn on the basis of the data. Since achievement of desirable terminal conditions along the line of sight was the most difficult part of the docking task, the use of

near-minimum control inputs and long time intervals between inputs may have particular influence on the values for longitudinal velocity. In addition, the velocity boundaries invariant with range for all three velocity components shown in figure 9 are parallel to, but exceed in magnitude, curves for a minimum control input. (For the same controllers used herein, ref. 6 shows minimum control inputs of about 0.1 sec.)

Summary curves of the terminal measurements for the two tanks are presented in figure 10. Some reduction in the maximum values shown may be anticipated as a result of an increase in pilot proficiency with additional training. If the 90-percent level is arbitrarily selected as an upper limit for a proficient pilot, typical maximums to be expected are as follows:

Normal to line of sight:

Transverse misalignment

$$\frac{y_{t,v}}{D} \text{ or } \frac{z_{t,h}}{D} \dots \pm 0.120$$

Transverse velocity

$$\frac{\dot{y}_{t,v}}{D} \text{ or } \frac{\dot{z}_{t,h}}{D} \dots \pm 0.010$$

Velocity docking direction

$$\frac{\dot{y}_{t,h}}{D} \text{ or } \frac{\dot{z}_{t,v}}{D} \dots \pm 0.028$$

Along line of sight:

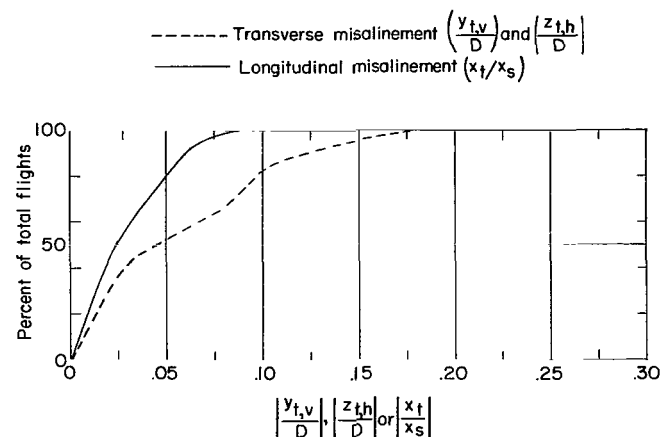
Longitudinal misalignment

$$\frac{x_t}{x_s} \dots \pm 0.060$$

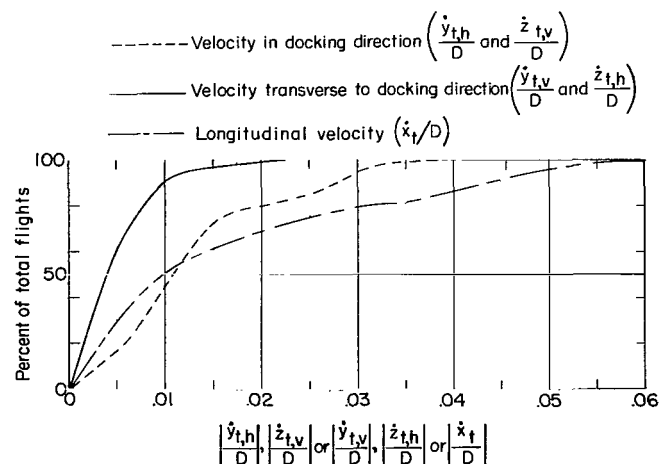
Longitudinal velocity

$$\frac{\dot{x}_t}{D} \dots \pm 0.045$$

The tabulated magnitudes of the two velocity components and the single displacement normal to the pilot's line of sight appear acceptable for remote sight docking. The values are similar to results previously encountered for two-vehicle docking involving a manned spacecraft and an orbiting vehicle (refs. 5 and 6). Of significance is the fact that the longitudinal velocity



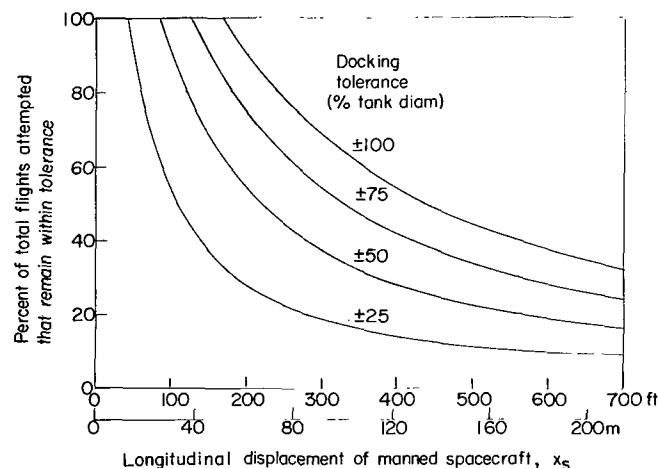
(a) Displacements (note difference in nondimensionalizing factors).



(b) Residual velocities.

Figure 10.- Summary curves of terminal conditions for maneuverable tank relative to reference tank showing percentage of flights below a given magnitude.

between the two tanks is of small magnitude and appears independent of the distance from the manned spacecraft. Thus, the results for the three velocity components indicate that an upper limit to the energy exchange between tanks at contact is independent of the range of the manned spacecraft for the distances investigated. Pilots' judgments of tank longitudinal misalignment, however, deteriorate as the distance between the manned spacecraft and tanks increases. Since, for a given coupler design, a maximum longitudinal displacement error will be specified, the results presented herein indicate that a range limitation for the manned spacecraft exists if the ability to dock the tanks is to be maintained at a high level of success. At ranges greater than this limiting value, the percentage of successful completions will decrease. Figure 11 illustrates the variation between docking success and manned spacecraft range for a trained pilot for various maximum longitudinal misalignment errors permitted by a docking apparatus. When the separation distance between spacecraft and tanks must be large (greater than 200 feet or 60 meters), the use of a docking technique that does not require nulling longitudinal misalignment errors but permits some latitude in this variable (capture on a slow fly-by) may eliminate the difficulties of the present technique yet retain unaided visual observation of the vehicles for guidance. In addition, the use of aids for visual amplification such as stadiametric ranging devices or the incorporation of radar instrumentation would undoubtedly eliminate the trade-off between docking success and manned spacecraft range indicated by the present data. Because of the magnitude of the numbers labeling the curves of figure 11, it is of interest to consider briefly the possible appearance of a docking device designed on the basis of the present data. Compared to the conical frustums for the probe



and drogue arrangement used for the actual space flights of the Gemini and Agena vehicles, a similar drogue device used on the reference tank would have to be elongated considerably in the longitudinal direction.

Fuel and Flight-Time Considerations

Inasmuch as desirable terminal conditions were of primary importance for the docking task, no restraints were placed on fuel and flight time. Fuel and flight-time results are of interest, however, because these values represent the cost of task accomplishment.

Total fuel values, expressed in terms of characteristic velocity ΔV , are presented in figure 12 as a function of flight time. The data show a trend of an increase in ΔV with increasing flight time. Examination of component data (not presented) for the manned spacecraft and for the maneuverable tank separately showed a similar trend in each component. Two possible reasons for the general data trend are apparent; the effect results either from additional maneuvering of the spacecraft and tank or from the different initial conditions used for the flights. Since the latter factor can be easily examined analytically, theoretical minimum fuel calculations were made for each flight in order to account for differences in initial velocities and displacements. The calculated values represent the minimum fuel required for translating the two vehicles from the initial conditions to actual terminal values in the recorded flight time. These values when plotted in figure 12 are less than the corresponding flight values and fall within the shaded region shown.

(Note that the upper and lower calculated boundaries used in fig. 12 are actual variations of ΔV with flight time for two different sets of initial conditions and are typical of the different shapes of the theoretical curves for the initial conditions employed.) Since the shaded region does not show a trend similar to the data, differences in initial conditions can be eliminated as a possible explanation. Extra spacecraft and tank maneuvering, consequently, are responsible for producing the data trend.

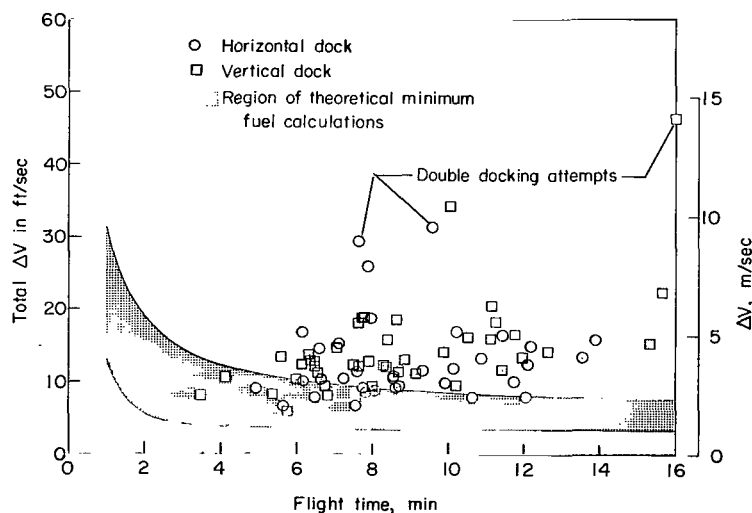


Figure 12.- Comparison of measured and calculated values of total fuel consumption (in terms of characteristic velocity increment ΔV) as a function of flight time.

Extra maneuvering can arise during a flight as a result of

- (1) Corrections made near flight termination to achieve desired end conditions
- (2) Inefficiency in performing necessary translations for gross position changes
(the use of a nonoptimum flight plan)

The first factor is probably the largest contributor to differences between individual measured and calculated values of ΔV and is the factor producing the general trend of an increase in ΔV with flight time. Corrective control inputs near flight termination are numerous and are required frequently because displacement errors are continuously generated by ever-present unnullled residual velocities. The few large values of ΔV shown in figure 12 are known to correspond to double docking attempts wherein the first docking attempt was stopped, the spacecraft and tanks realigned, and the docking maneuvers carried out a second time.

When the ΔV components for the manned spacecraft and maneuverable tank were examined separately, the following observations were also apparent. For comparable initial velocities and distances traversed,

- (1) Scatter in the ΔV -data for a given flight time was larger for the tank than for the spacecraft
- (2) The magnitudes of the ΔV -data were larger for the tank than for the spacecraft
- (3) The ratios of measured to calculated ΔV were larger for the tank than for the spacecraft

These effects were as expected because the primary task was docking between spherical tanks. Figure 13 illustrates some of these effects and summarizes the ΔV and flight-time measurements obtained.

Supplemental Tests

Range meters installed. - Since the principal difficulty in achieving successful remote docking of two tanks at the larger distances from the manned spacecraft was associated with judgments of size, a few docking flights were made with the addition of cockpit instrumentation. Two single-hand range meters were installed side by side on the center instrument panel to display the distances between the manned spacecraft and each spherical tank. The resolution of the range meter was of the order of 1 foot (0.3 meter). Six simulator flights were made with the manned spacecraft positioned about 200 feet (60 meters) and six flights at about 300 feet (90 meters) from the two tanks at docking. With the range meters installed, longitudinal displacement between tanks at docking is no longer a function of manned spacecraft range but is limited either by meter resolution or by control sensitivity. As expected, the test results

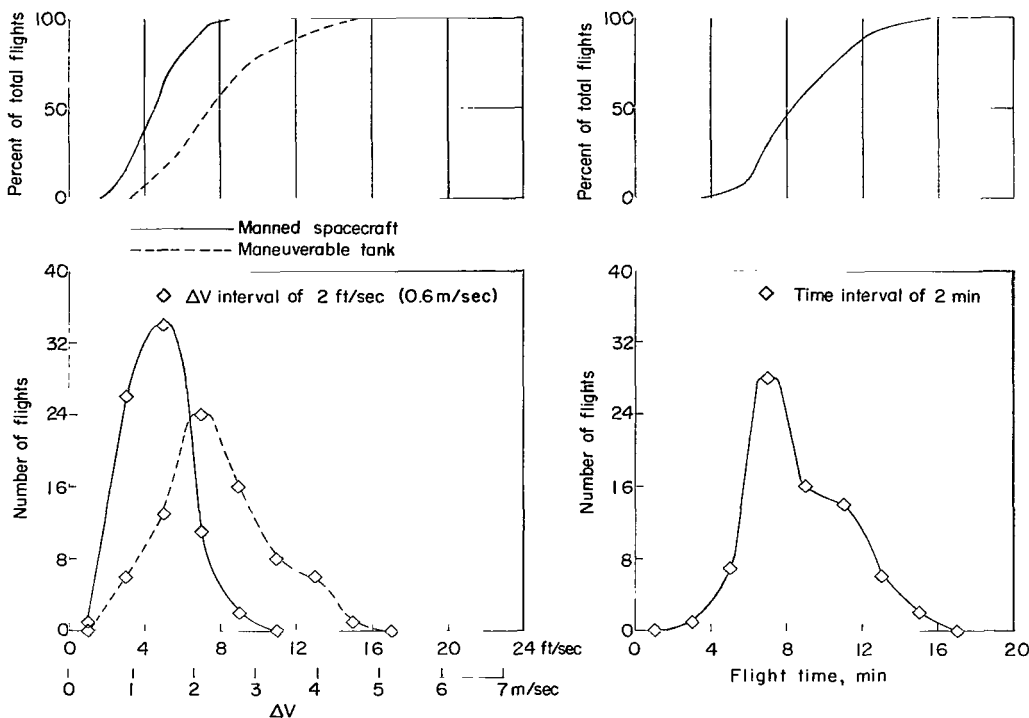


Figure 13.- Individual data summaries for spacecraft fuel, tank fuel, and flight time.
(Fuel consumption expressed as characteristic velocity increment ΔV .)

(not presented herein) show longitudinal displacement values between tanks considerably smaller than those of the basic investigation; however, magnitudes as large as 5 and 6 feet (1.5 and 1.8 meters) were obtained for several flights. Pilots used the range meters not only for longitudinal displacements but also for determining longitudinal velocities. Division of attention between the instrumentation and visual display and the time spent in estimating closure rates permitted larger displacements to build up in the visual display variables normal to the pilot's line of sight. The time spent in performing these final corrections contributed directly to the 5- and 6-foot (1.5- to 1.8-meter) longitudinal displacement errors at flight termination.

With the range meter installation, pilots easily positioned the manned spacecraft at about the desired range from the reference tank and, in addition, permitted only a very low spacecraft closure rate to exist (0.13 ft/sec or 0.05 m/sec maximum). Residual longitudinal velocity between tanks was reduced. Further examination of the data indicated magnitudes for velocities and displacements normal to the pilot's line of sight to be within the approximate data boundaries shown for the basic investigation. With a better instrument display that included range-rate information, some improvement might be obtained in these particular terminal conditions.

It is worth noting that even with the addition of instrumentation, the pilots employed the same guidance technique for obtaining gross alinement of the three vehicles and used the instruments only for achieving desired terminal conditions. Recorded flight times were between 5 and 10 minutes and fuel consumption values were within the scatter shown for the basic data of figure 12.

Partial lighting.- The circular light spots of the basic investigation represented a physical situation in which the spherical tanks were illuminated in a direction approximately along the pilot's line of sight. However, the size and shape of the visually observable illuminated portions of spherical tanks can vary over a wide range depending on the direction of illumination relative to the pilot. For most partial lighting configurations,

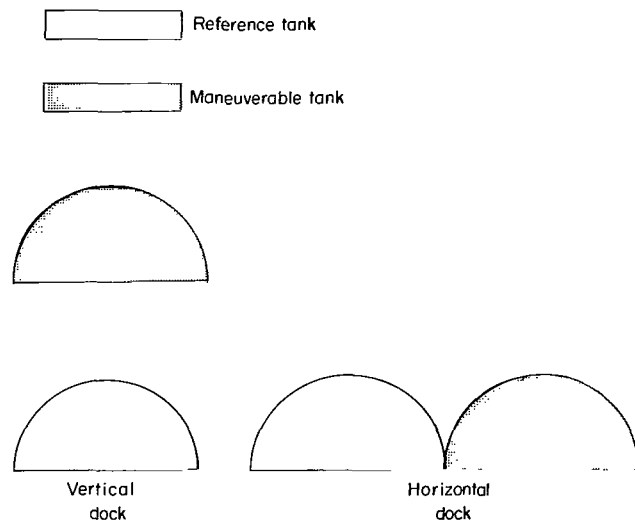


Figure 14.- Partial-lighting configurations.

degradations in terminal conditions with increases in fuel and flight-time performance levels can be expected. Therefore, some additional flights were performed in which tank illumination was arbitrarily chosen in a direction normal to the pilot's line of sight. In this lighting situation, the spherical tanks would appear as half-circular light spots. (See fig. 14.) Simple masks over the mechanical apertures were employed in the test setup and both horizontal and vertical dockings were attempted. Vertical dockings, although not exactly representative of a specific lighting condition, did introduce an additional factor into the piloting task that could occur in an actual orbital situation,

that of separation between illuminated areas of the tanks at flight termination. Examination of the data (not presented herein) from 9 vertical dockings and 9 horizontal dockings indicated:

(1) Magnitudes for each variable were within the approximate boundaries shown for the corresponding variable of the basic data. (Differences due to vertical and horizontal dockings were not discernible.)

(2) The fuel consumption as a function of flight-time results were within the normal spread of data of the basic investigation. (For 3 of the 18 flights, fuel and flight-time values were obtained that approximated the data for double docking attempts shown in fig. 12.)

These few flight results indicate that, of the large variety of possible partial lighting configurations, some lighting conditions do exist in which sizable reductions in the observable illuminated area of the two tanks can occur without influencing the docking results.

CONCLUSIONS

A brief docking study of a three-vehicle system has been made on a fixed-base simulator to determine the ability of human pilots to perform orbital docking between two vehicles from a manned spacecraft positioned some distance away. All three vehicles were assumed to be attitude stabilized. The pilot was given translation control of the manned spacecraft and one of the remotely located vehicles by means of simple on-off reaction jets. The remaining vehicle was assumed nonmaneuverable. The information display consisted of two light spots projected on a cylindrical screen and symbolized two fully illuminated spherical tanks. Guidance information was obtained from visual observation of the projected display, and docking was considered complete when the two light spots were of the same size and tangent to each other. The results of the investigation apply to a docking condition in which both fully illuminated tanks were positioned directly in front of the pilot at contact and are as follows:

1. At flight termination, the transverse misalignments and the three velocity components between tanks were found to be invariant with manned spacecraft range for the distances investigated. The velocities were also found to be of small magnitude. Thus, an upper limit to the energy exchange between tanks at contact was indicated irrespective of the distance away of the manned spacecraft.

2. Longitudinal misalignment of the two tanks at docking increased as the distance of the manned spacecraft from the two tanks was increased. For a given size docking mechanism, this result can be interpreted as a decrease in docking success with an increase in manned spacecraft range. At the larger manned spacecraft ranges, the use of visual aids, instrumentation, or a different docking technique appeared necessary to maintain a high percentage of successful completions.

3. Transverse displacements and residual velocities of the manned spacecraft at flight termination were within acceptable magnitudes to permit docking of the two tanks.

4. Some increase in fuel used was obtained with an increase in flight time. The effect was attributed to the additional maneuvering necessary for achievement of desired terminal conditions and to the frequent control inputs required near flight termination for correction of displacement errors that were continuously being generated by unnullled residual velocities.

5. A few flights made with partially illuminated spherical tanks indicated that of the large number of possible partial lighting conditions, large reductions in the illuminated

area visible to the pilot can occur for specific lighting configurations without producing a degradation in terminal conditions or performance levels.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., May 8, 1967,
125-17-05-01-23.

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